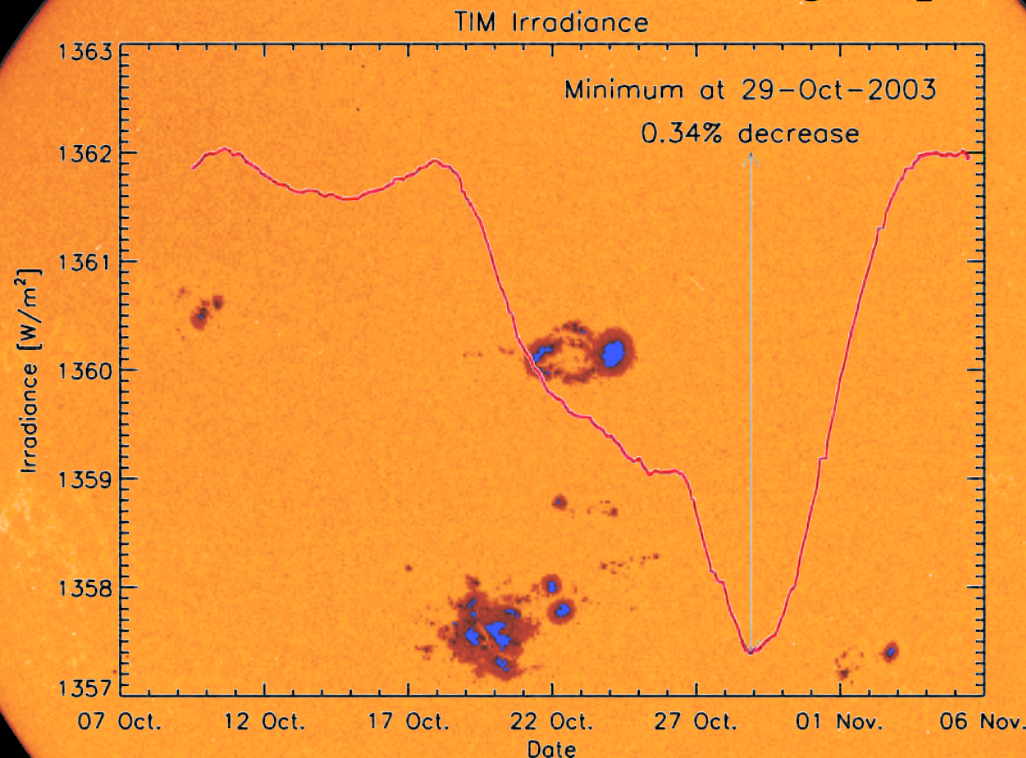


# Current Calibration Capabilities for Solar Irradiance Instruments

Greg Kopp  
& LASP Solar Irradiance group



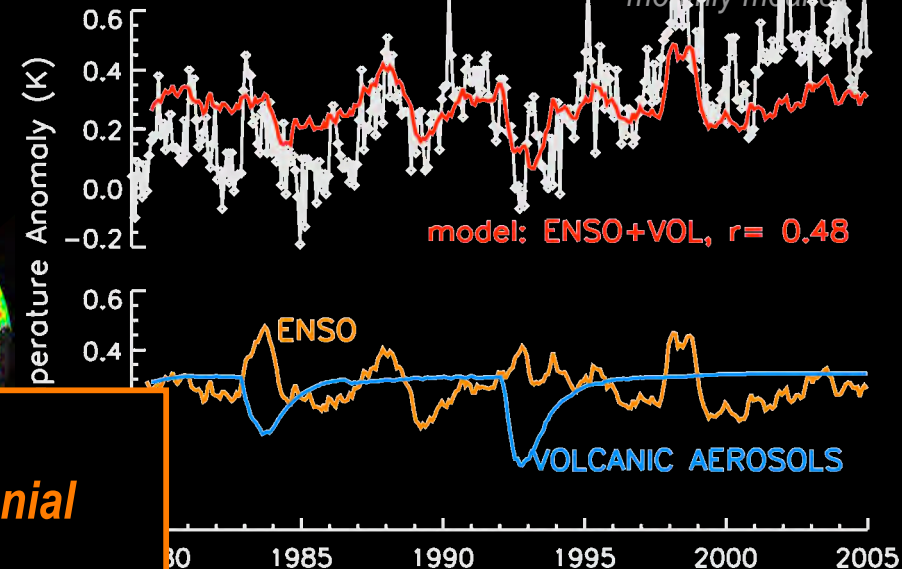
Laboratory for Atmospheric and Space Physics  
University of Colorado  
1234 Innovation Dr., Boulder, CO 80303, USA  
Greg.Kopp@LASP.Colorado.edu

# Solar and Anthropogenic Climate Signals

GISS Land+Ocean Global Temperature

from Judith Lean, NRL

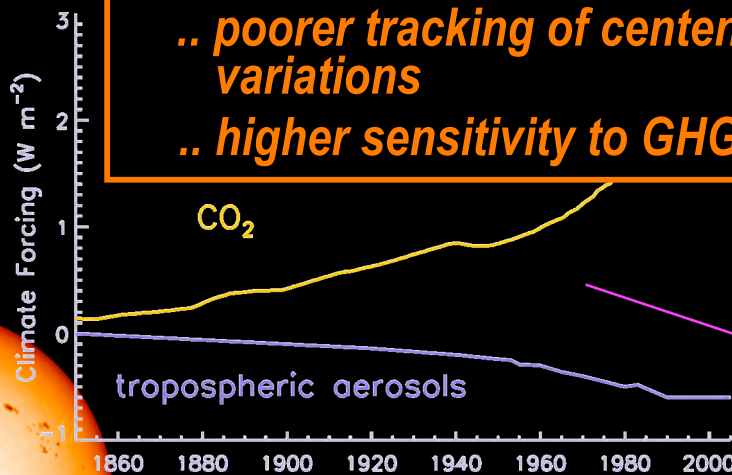
monthly means



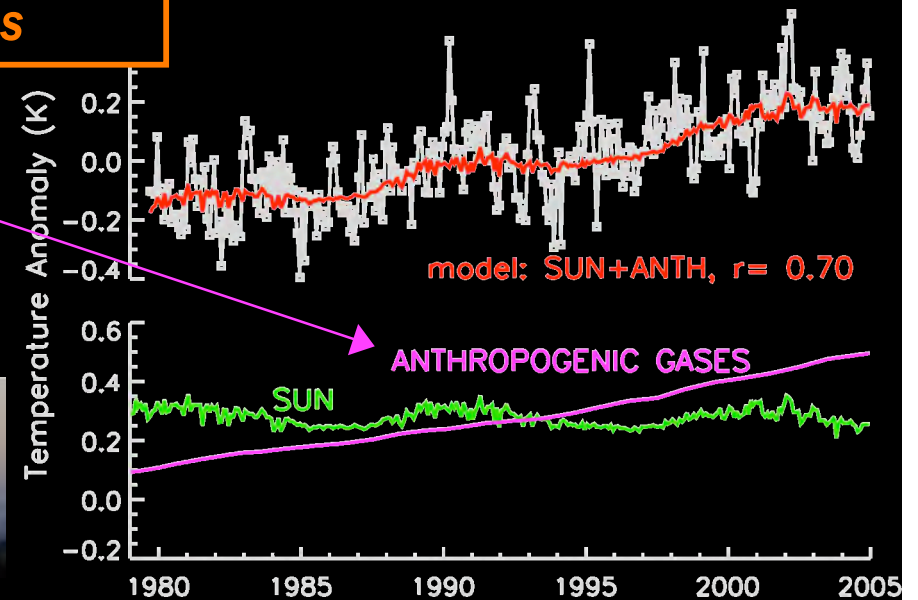
omitting solar forcing →

.. poorer tracking of centennial variations

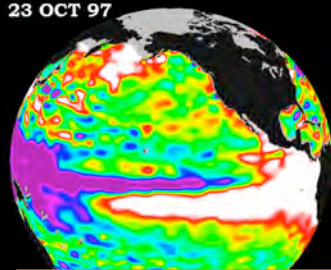
.. higher sensitivity to GHGs



greenhouse gases  
industrial aerosols

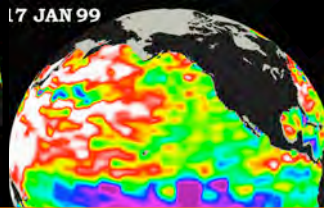


El Nino



23 OCT 97

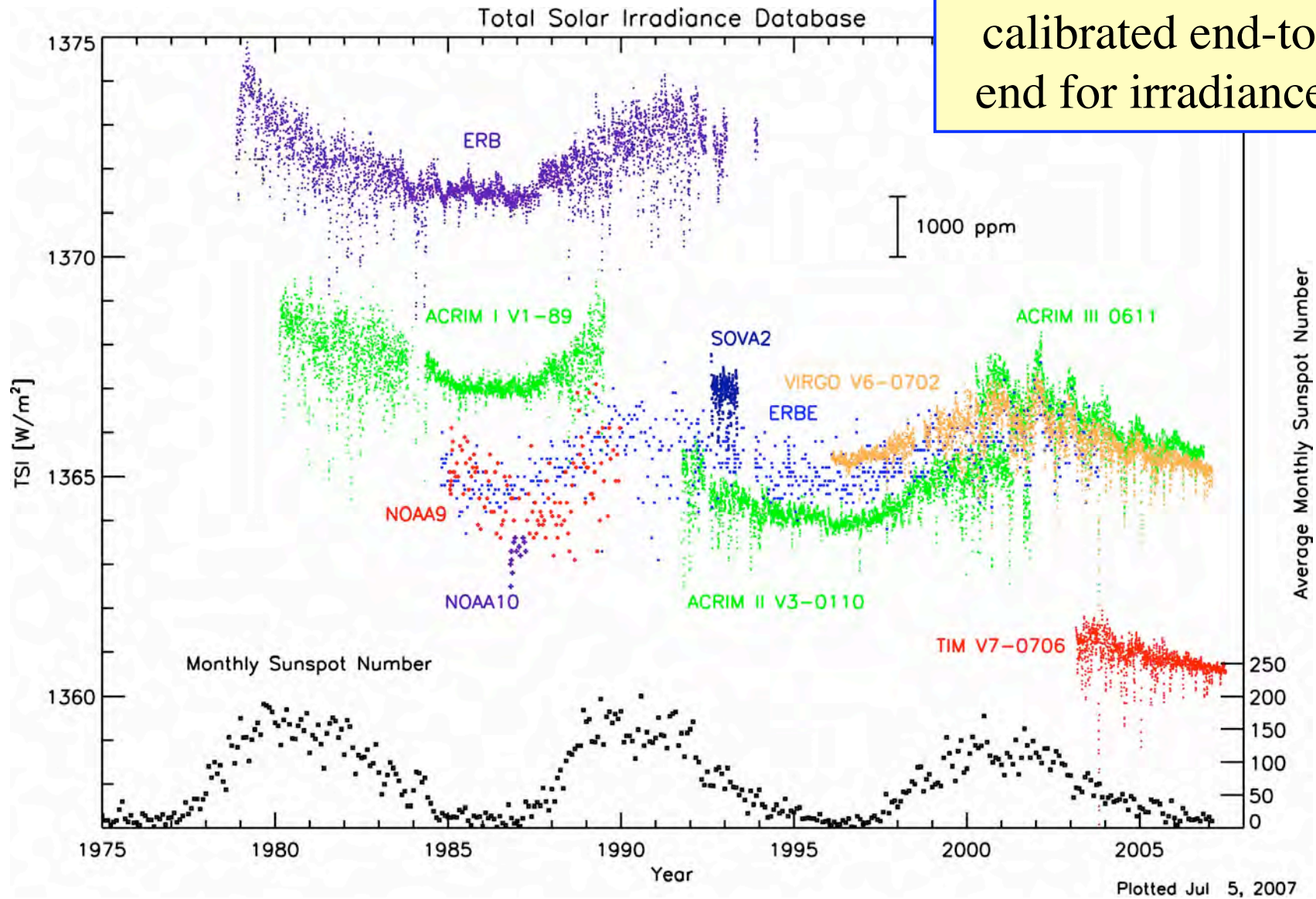
La Nina



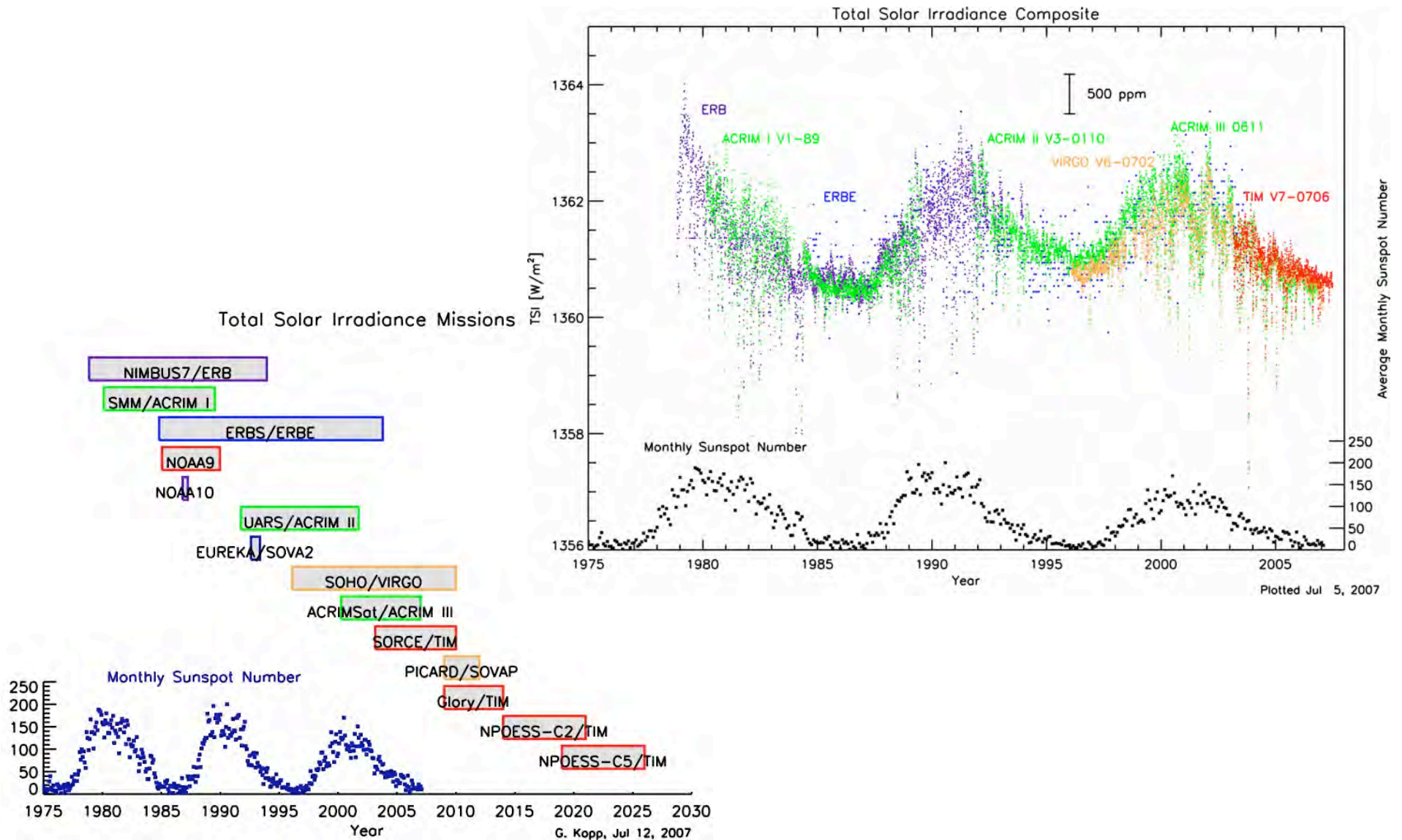
17 JAN 99

## TSI Climate Record ~30 Years

None of these instruments is calibrated end-to-end for irradiance.

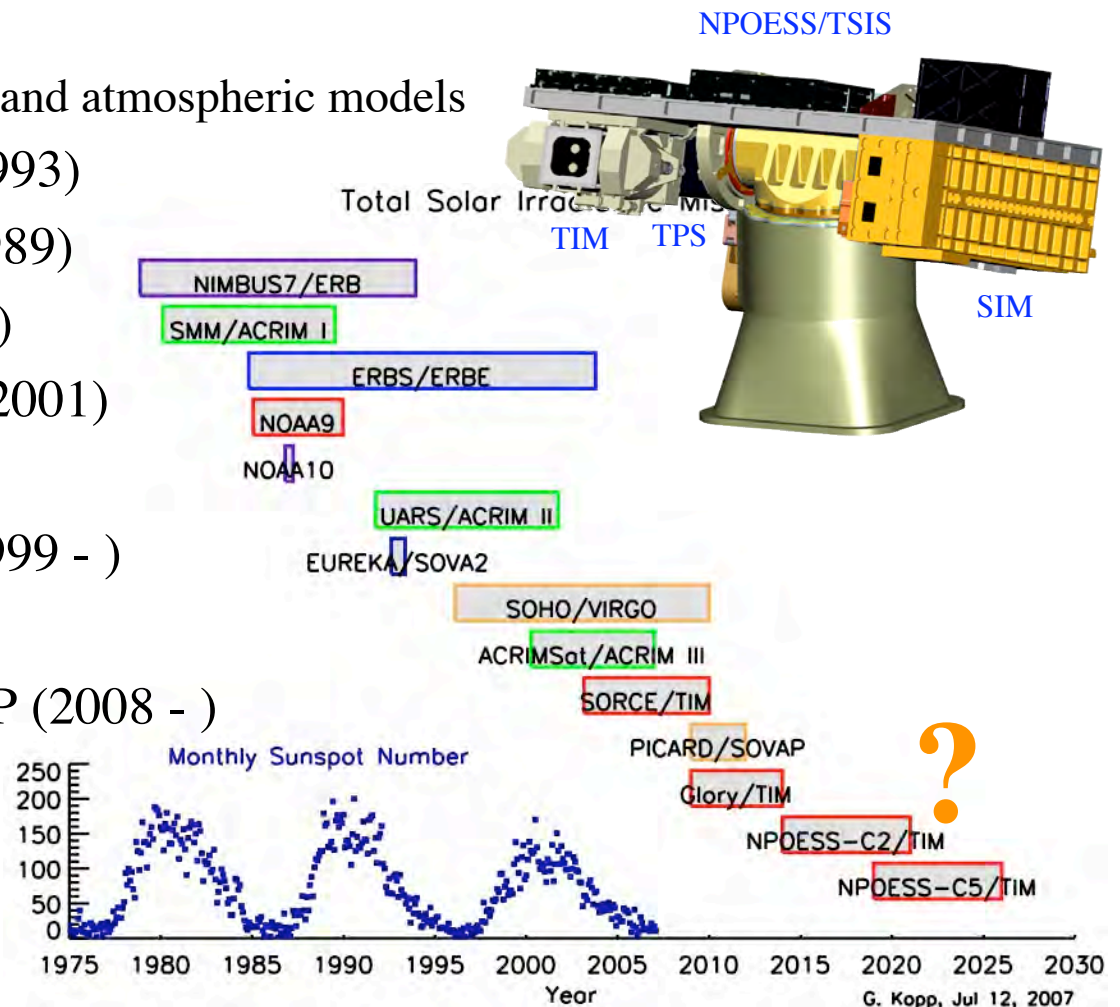


# TSI Record Has Relied on Continuity



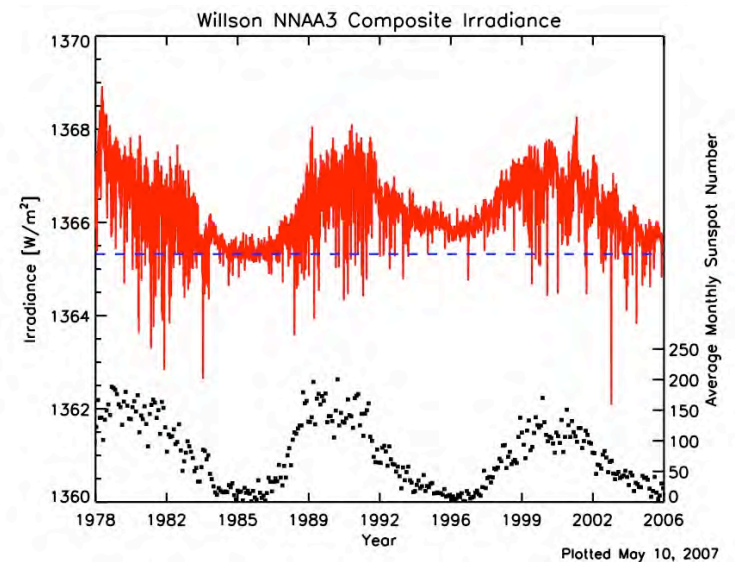
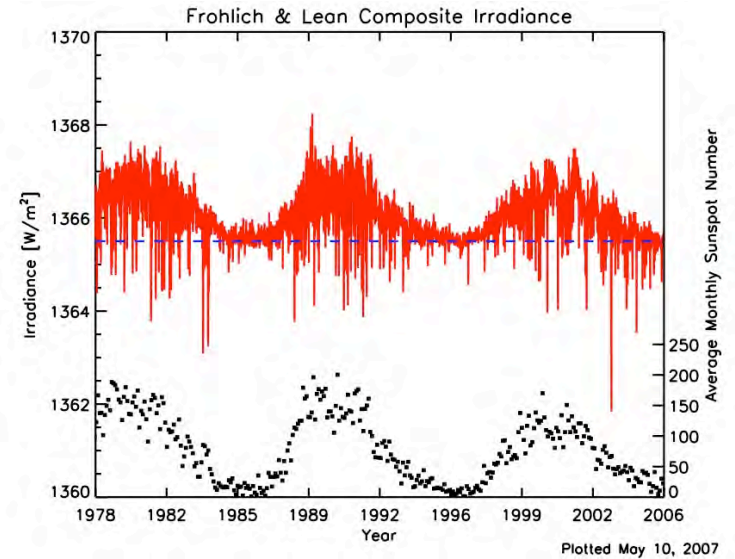
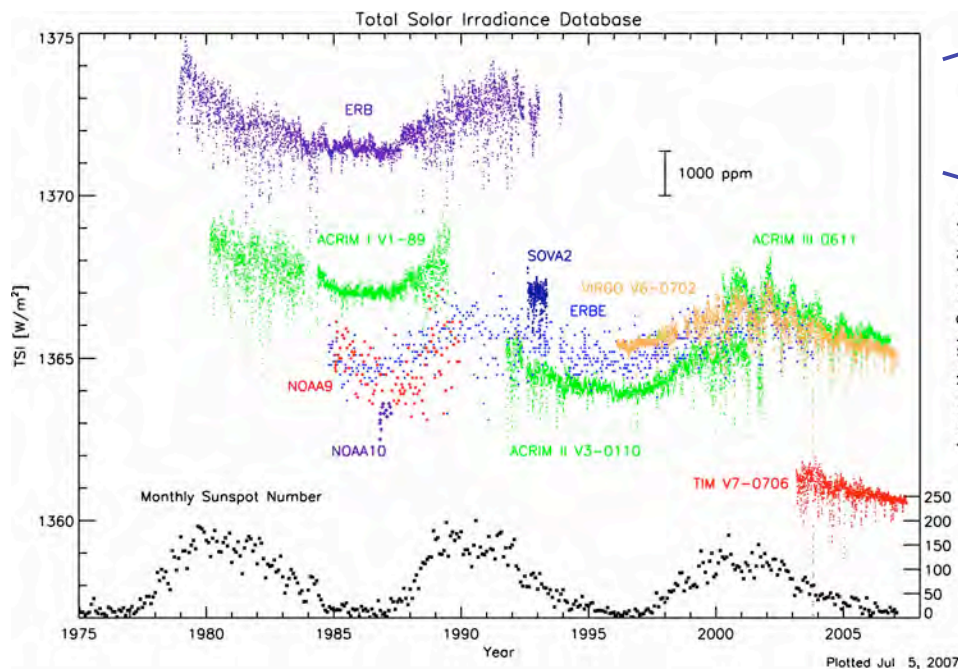
# Solar Total Irradiance Measurement Summary

- Continuous and overlapping measurements are critical in maintaining a long term data record.
  - Critical for climate
  - Useful for inputs to solar and atmospheric models
- NIMBUS7 ERB (1978 - 1993)
- SMM ACRIM I (1980 - 1989)
- ERBS ERBE (1984 - 2003)
- UARS ACRIM II (1991 - 2001)
- SOHO VIRGO (1996 - )
- ACRIMSat ACRIM III (1999 - )
- SORCE TIM (2003 - )
- PICARD PMO6 & SOVAP (2008 - )
- Glory TIM (2008 - )
- NPOESS? TIM (2013 - )



# Composites Rely on Continuity *and* Stability

Two primary TSI composites differ by 40 ppm/yr caused by 2 years of marginal quality data – not even a gap!



# Future Needs: TSI – Accuracy and Stability

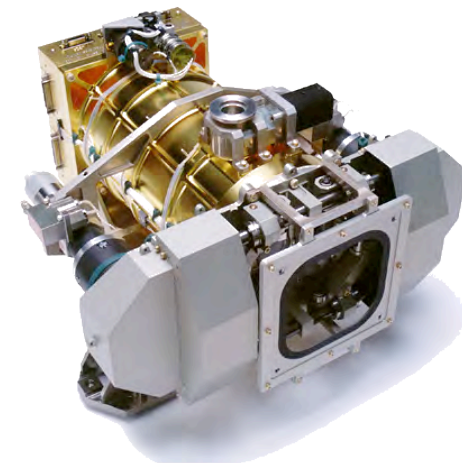
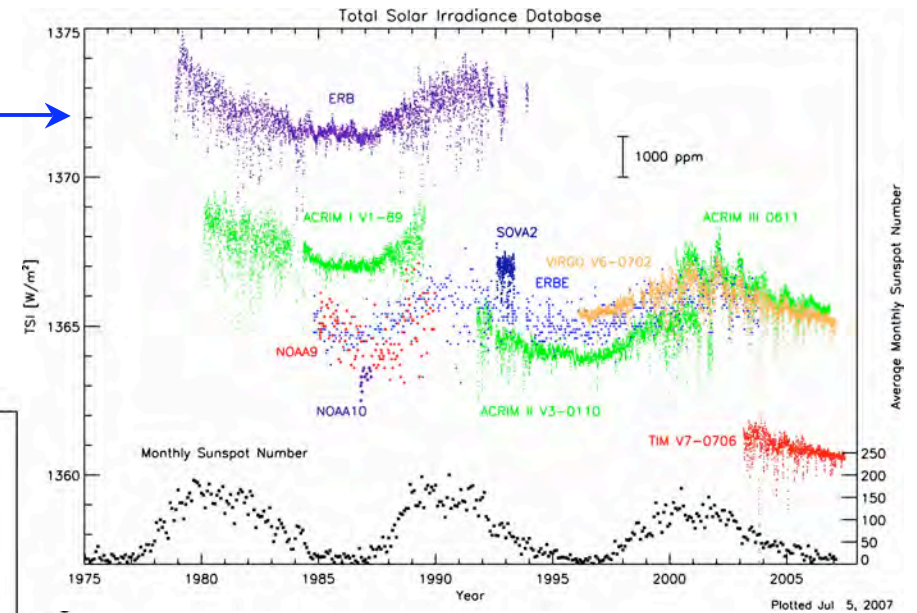
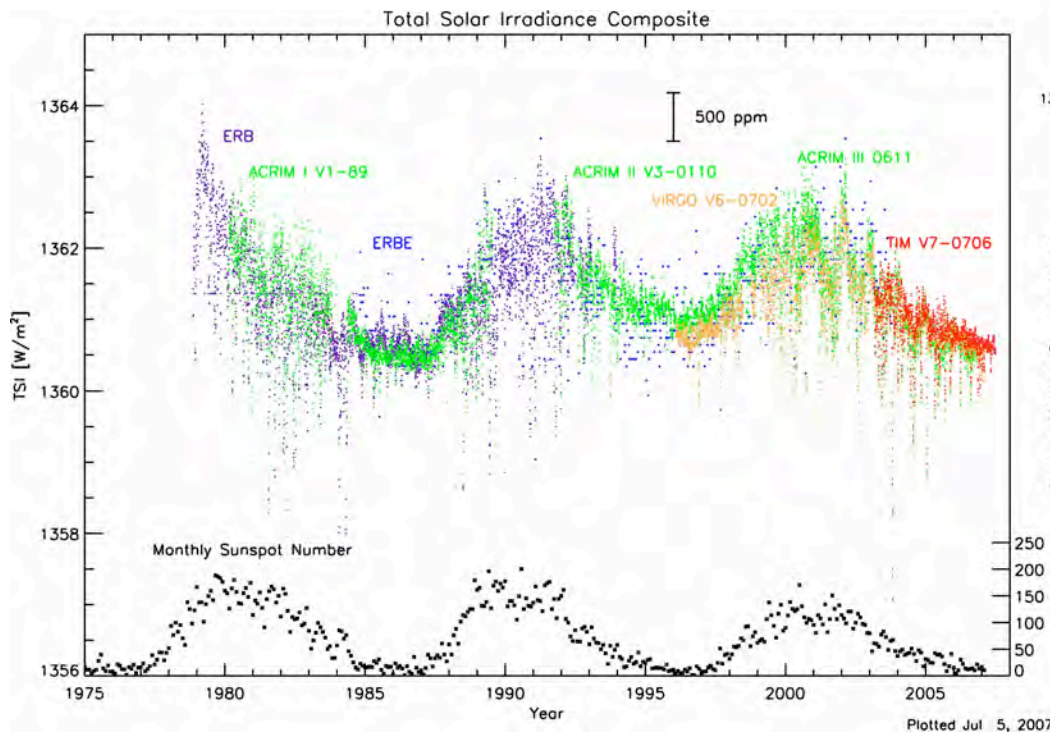
- Performance Requirements

- Accuracy
- Stability
- Noise

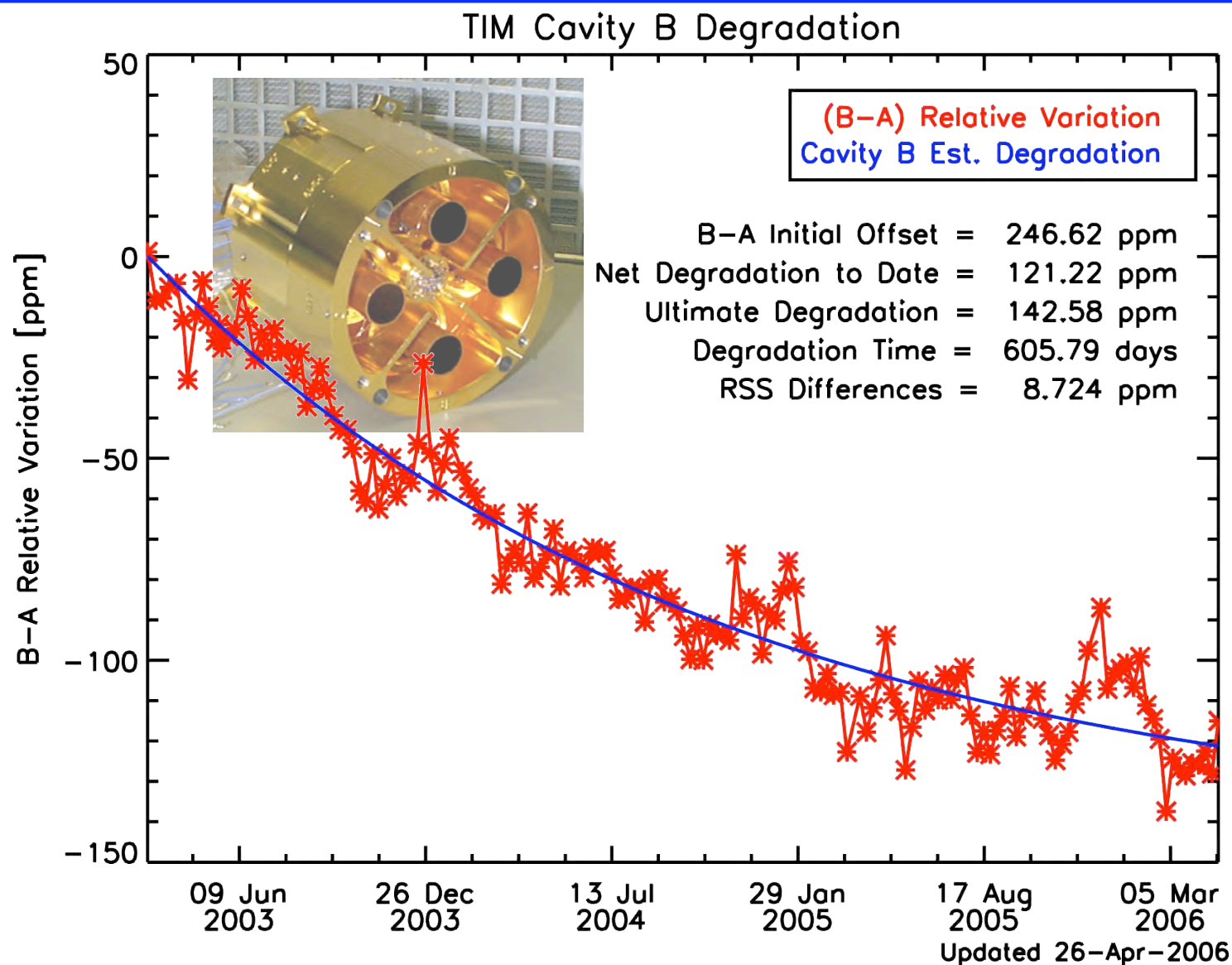
0.01% ( $1\sigma$ )

0.001%/yr ( $1\sigma$ )

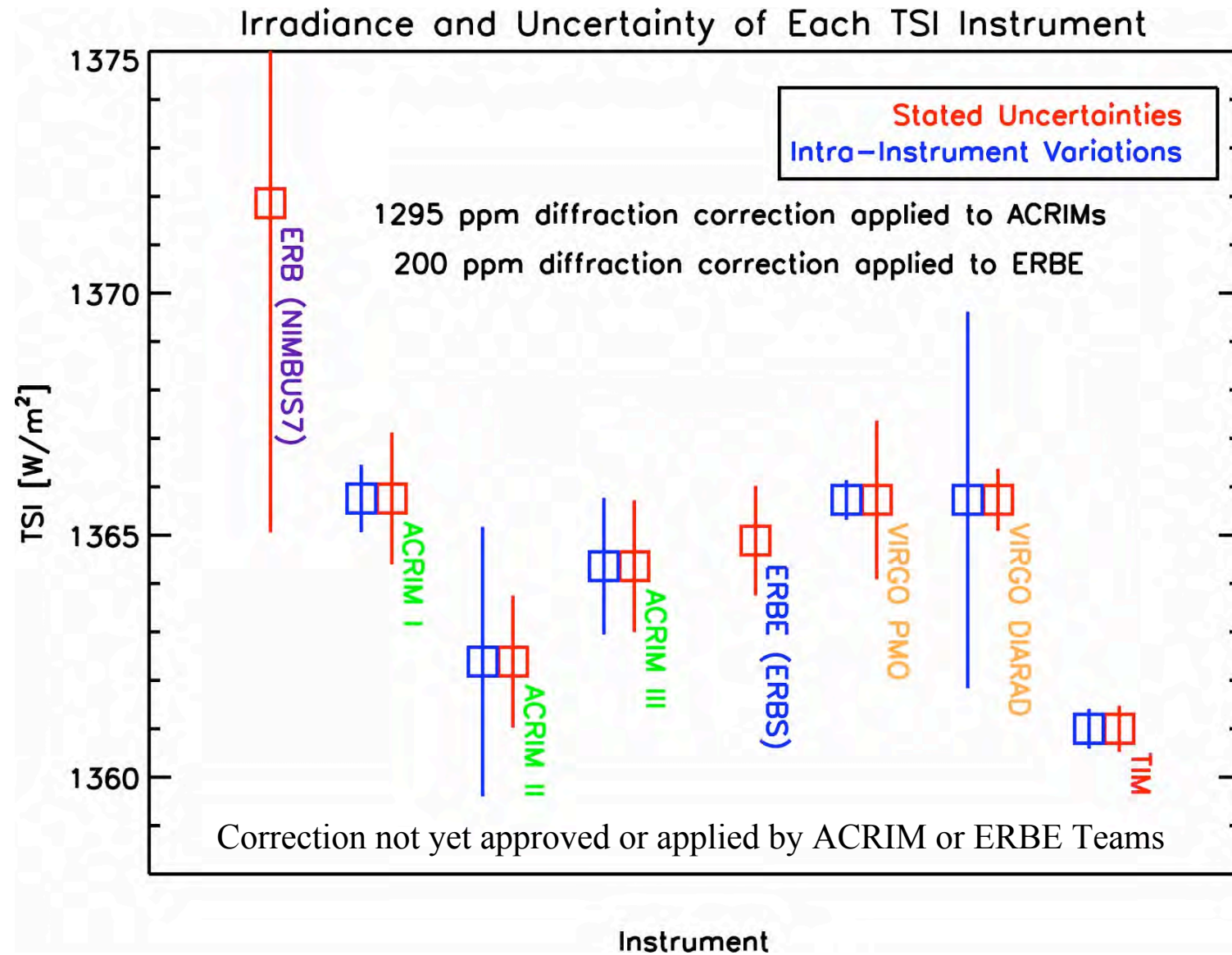
0.001% ( $1\sigma$ )



# Stability Has Been Achieved by Duty Cycling Radiometers



# TSI Instrument Uncertainties – With Diffraction Correction



# Instrument Uncertainties Determined at the Component Level

## SORCE/TIM

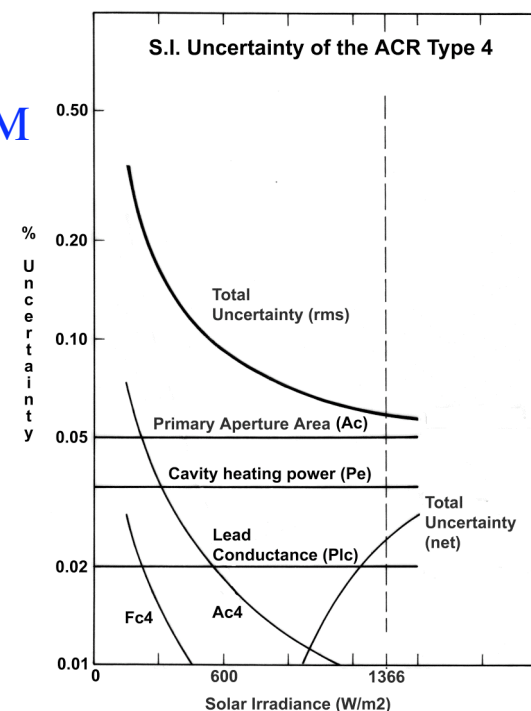
Correction	Value [ppm]	$\sigma$ [ppm]
Distance to Sun, Earth & S/C	33,537	0.1
Doppler Velocity	57	0.7
Shutter Waveform	100	1.0
Aperture	1,000,000	30
Diffraction	452	46
Cone Reflectance	250	54
Non-Equivalence, ZH/ZR - 1	7, AC	23
Servo Gain	16,129	0.0
Standard Volt + DAC	1,000,000	7.0
Pulse Width Linearity	1,000,000	186
Standard Ohm + Leads	1,000,000	17
Dark Signal	2,693	10
Scattered Light & IR	100	25
Pointing		10
Measurement Repeatability (Noise)		1.5
Uncertainty due to Sampling		12
<b>Total RSS</b>		<b>206</b>

## VIRGO/PMO

### Uncertainty of the PMO6V WRR/SI traceability @ 1400W/m2

Component	Value	u	c	$(u \cdot c)^2$
Area	N/A			
Pclosed	45 mW	0.0000045	5.00E+04	0.050625
Popen	17 mW	0.0000017	5.00E+04	0.007225
CNE	1	5.00E-04	1.40E+03	0.49
CR	N/A	7.00E-05	1.40E+03	
CSt	N/A	1.00E-04	1.40E+03	
CLH	N/A	3.00E-05	1.40E+03	
CApH	N/A	5.00E-04	1.40E+03	
Cdiff	N/A	1.00E-04	1.40E+03	
WRR-Factor	1	6.00E-04	1.40E+03	0.7056
WRR/SI	1	9.00E-04	1.40E+03	1.5876
				2.84105
		Uncertainty abs		1.6855 W/m2
		Uncertainty rel		1685.5 ppm
		95% Uncertainty		3371.1 ppm

## ACRIM



## VIRGO/DIARAD L

	Relative	W/m2
Area	0.000425	0.58
Thermal efficiency	0.000130	0.18
Electrical. Power	0.000150	0.20
Cavity absorption	0.000030	0.04
<b>Total</b>	<b>0.000735</b>	<b>1.00</b>
RSS	0.000470	0.64

## Ground Calibration Improvements Lower Glory Uncertainties

- Glory/TIM has lower uncertainties than SORCE/TIM because of improved ground calibrations

Correction	Value [ppm]	$\sigma$ [ppm]	SORCE
Distance to Sun, Earth & S/C	33,537	0.1	0.1
Doppler Velocity	57	0.7	0.7
Shutter Waveform	100	1.0	1.0
Aperture	1,000,000	30	30
Diffraction	452	46	46
Cone Reflectance	250	51	54
Non-Equivalence, ZH/ZR - 1	7, AC	23	23
Servo Gain	16,129	0.0	0.0
Standard Volt + DAC	1,000,000	7	7.0
Pulse Width Linearity	1,000,000	6	186
Standard Ohm + Leads	1,000,000	17	17
Dark Signal	2,693	1.7	10
Scattered Light & IR	100	14	25
Pointing		10	10
Measurement Repeatability (Noise)		1.0	1.5
Uncertainty due to Sampling		12	12
<b>Total RSS</b>		<b>83.5</b>	<b>206</b>

Note dominant uncertainties are optical, and affect all solar radiometers

Largest calibration improvement

## TIM Requires “Subtle” Corrections

---

- Aperture knowledge accuracy

$$\frac{\Delta A}{A} = \frac{2\pi r \cdot \Delta r}{\pi r^2} = 10^{-4} \text{ (100 ppm)} \Rightarrow \Delta r = 200 \text{ nm}$$

- Doppler correction due to S/C orbit velocity

$$2 \frac{v}{c} = 2 \cdot \frac{8 \times 10^5 \text{ cm/s}}{3 \times 10^{10} \text{ cm/s}} \approx 5 \times 10^{-5} \Rightarrow \pm 50 \text{ ppm}$$

- Thermal (mid-IR) background

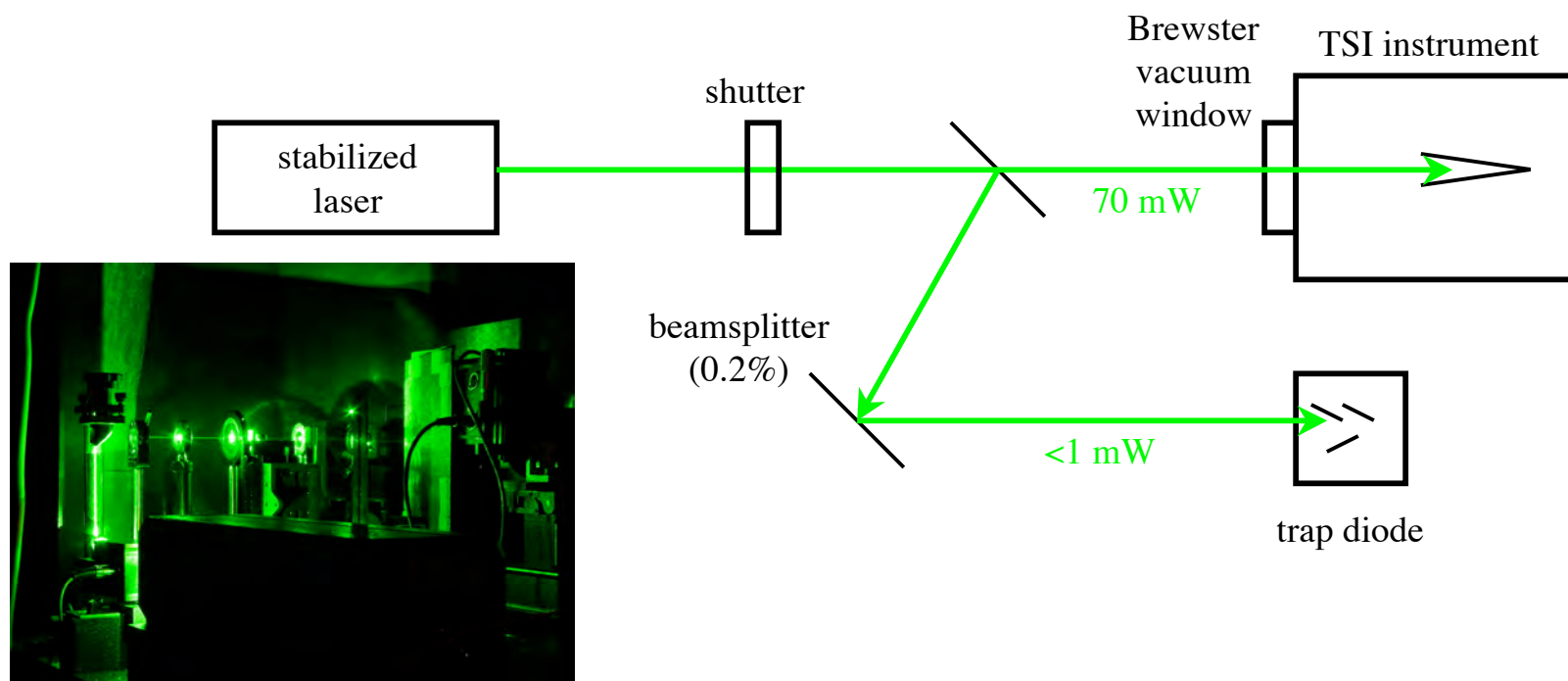
$$\sigma T^4 \cdot \text{Cone Entrance Area} = 8 \times 10^5 \text{ ergs} \Rightarrow 1.2 \times 10^6 \text{ ppm}$$

- Need “chopping,” or phase sensitive detection

*Instrument is characterized rather than calibrated  
for 100 ppm absolute standard uncertainty*

## Address Applied Power: Trap Diode Power Comparison

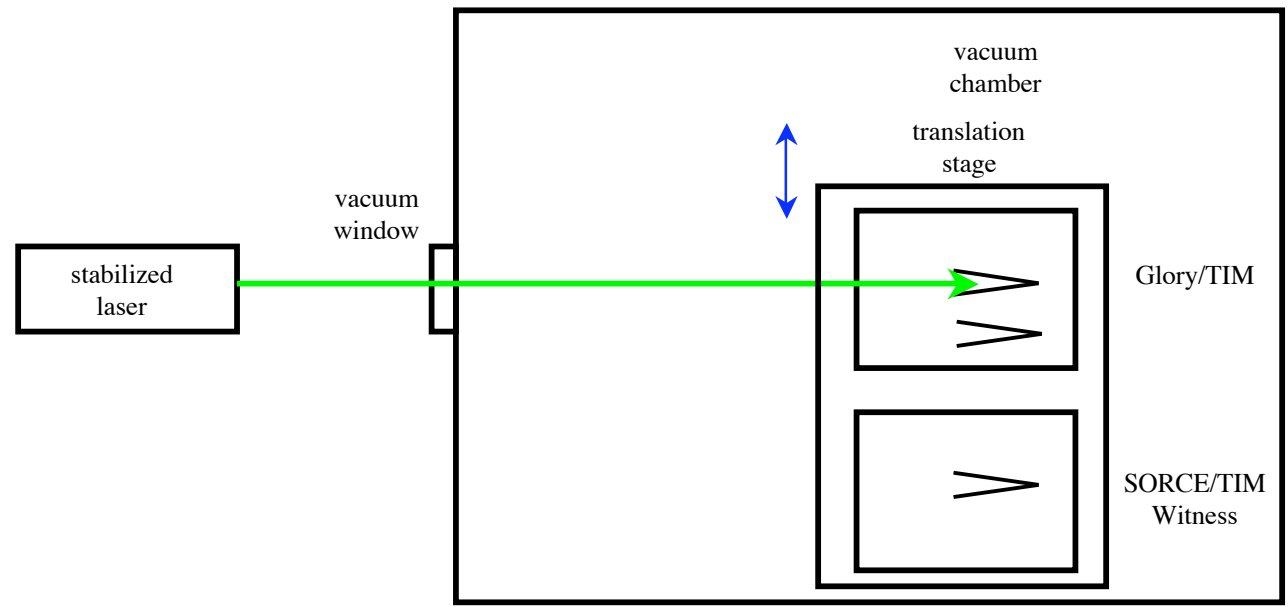
- This was a recommendation from the 2005 TSI Accuracy Workshop
- NIST and LASP performed optical power comparisons between a trap diode transfer standard and a ground-based TIM
  - Applying solar power levels with the TIM in vacuum
  - NPL has done similar power comparisons before



This is an optical power measurement, not irradiance

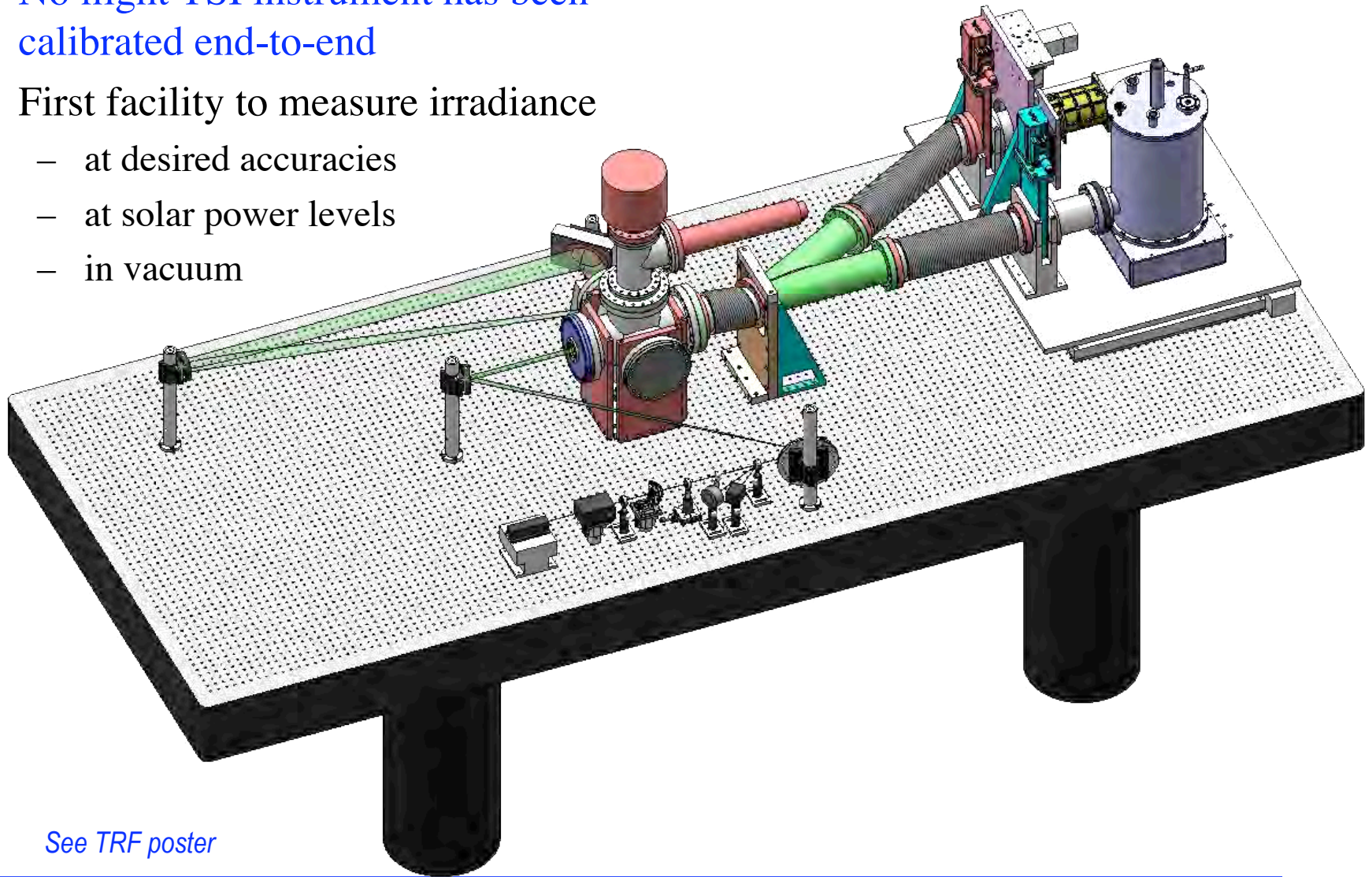
## Current Glory/TIM Optical Power Measurements

- Compare radiometer consistency within instrument
  - Preliminary results are consistent with  $\pm 0.01\%$  accuracy
- Compare Glory/TIM to SORCE Witness
  - Measures optical power only, not irradiance
  - SORCE Witness compared to trap diode at NIST in Nov. 2006



## TSI Radiometer Facility Measures *Irradiance*

- No flight TSI instrument has been calibrated end-to-end
- First facility to measure irradiance
  - at desired accuracies
  - at solar power levels
  - in vacuum



See TRF poster

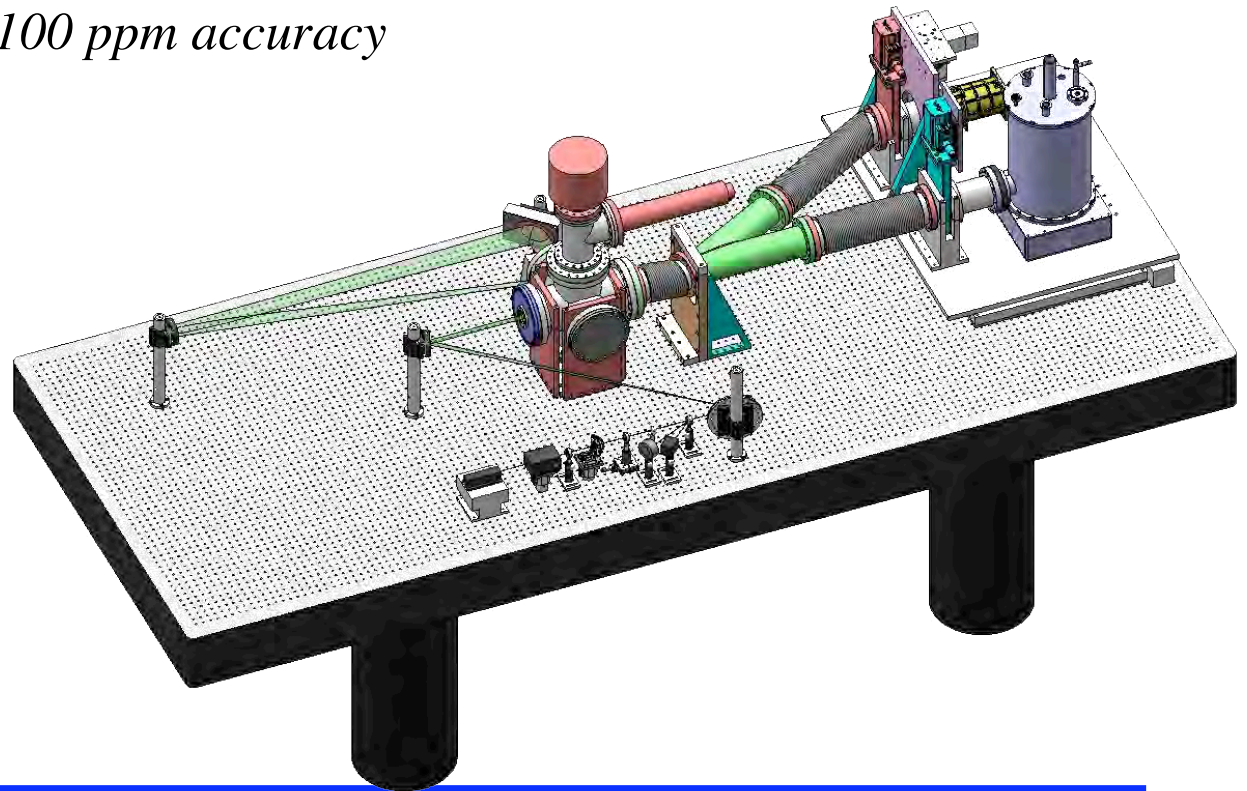
## TSI Radiometer Facility Measures *Irradiance*

---

The TRF will:

1. Improve the calibration accuracy of future TSI instruments,
2. Establish a new ground-based radiometric irradiance standard, and
3. Provide a means of comparing existing ground-based TSI instruments against this standard under flight-like operating conditions.

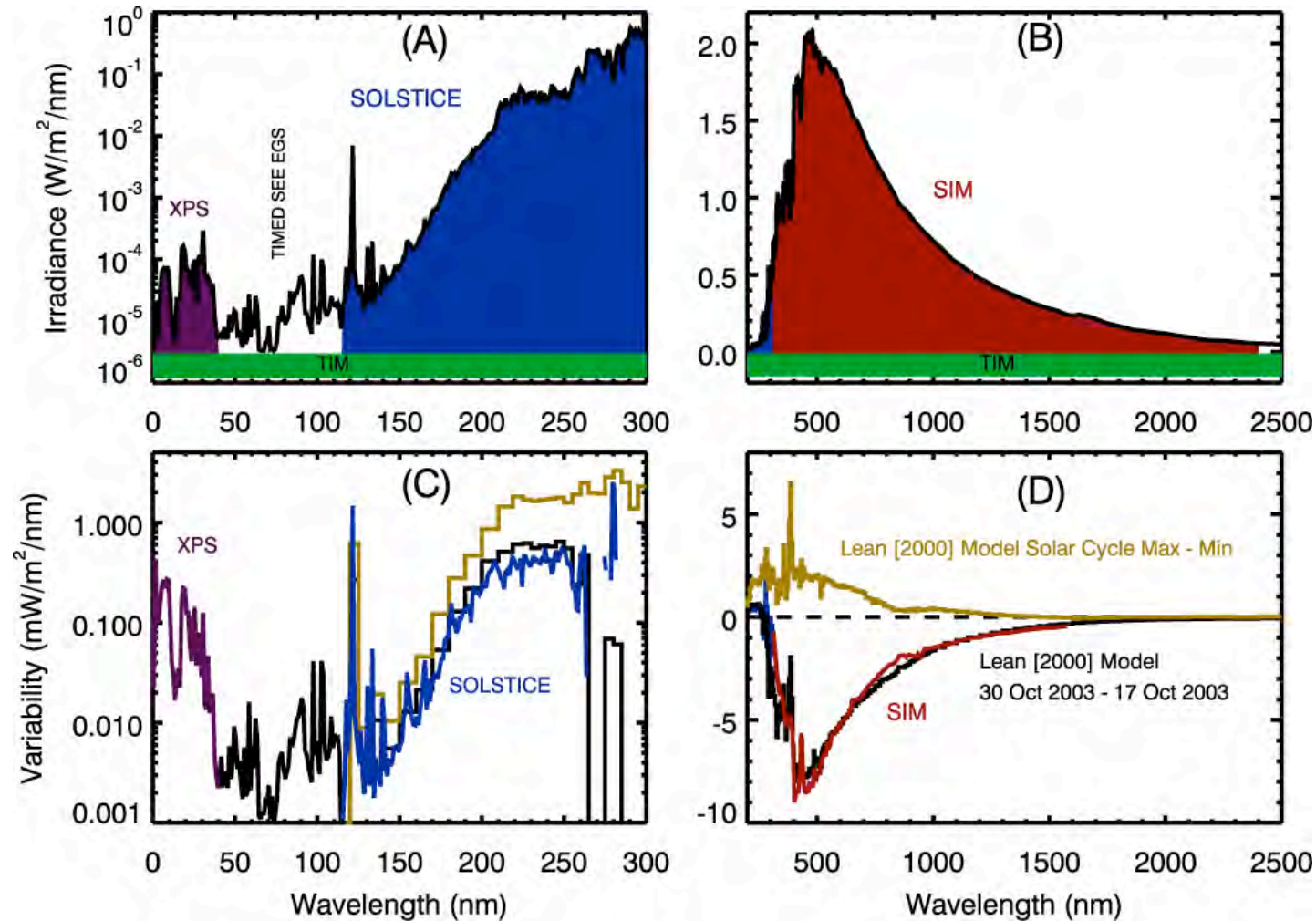
*Intended to achieve ~100 ppm accuracy*



*See TRF poster*

## Solar Variability Depends on Wavelength

SORCE and TIMED provide the first ever daily measurements of solar spectrum variations throughout the X-ray, UV, visible, and NIR



## Also Need Solar Spectral Irradiance Inputs

Near UV, visible, near infrared radiation affect surface and ocean processes

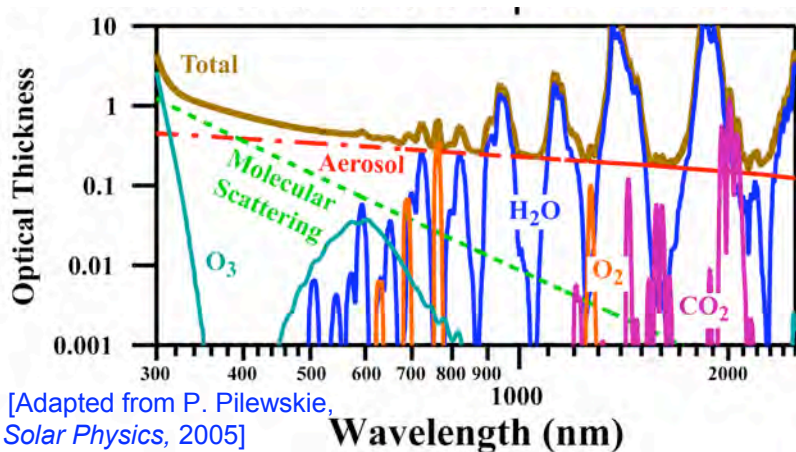
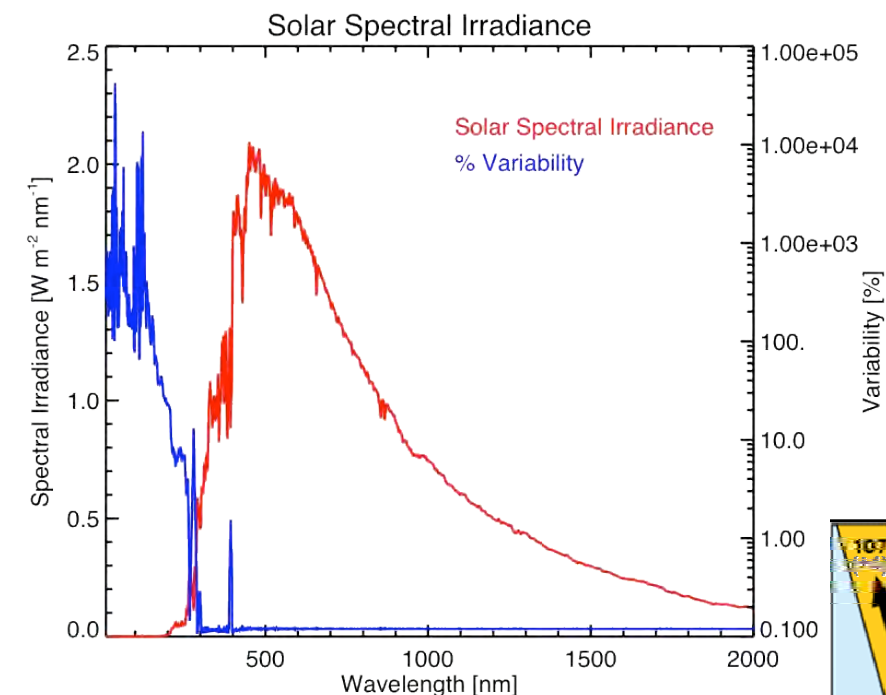
### Chemistry Climate Models Need SSI

GISS GCM [Rind et al., 2004; Shindell et al., 2006]

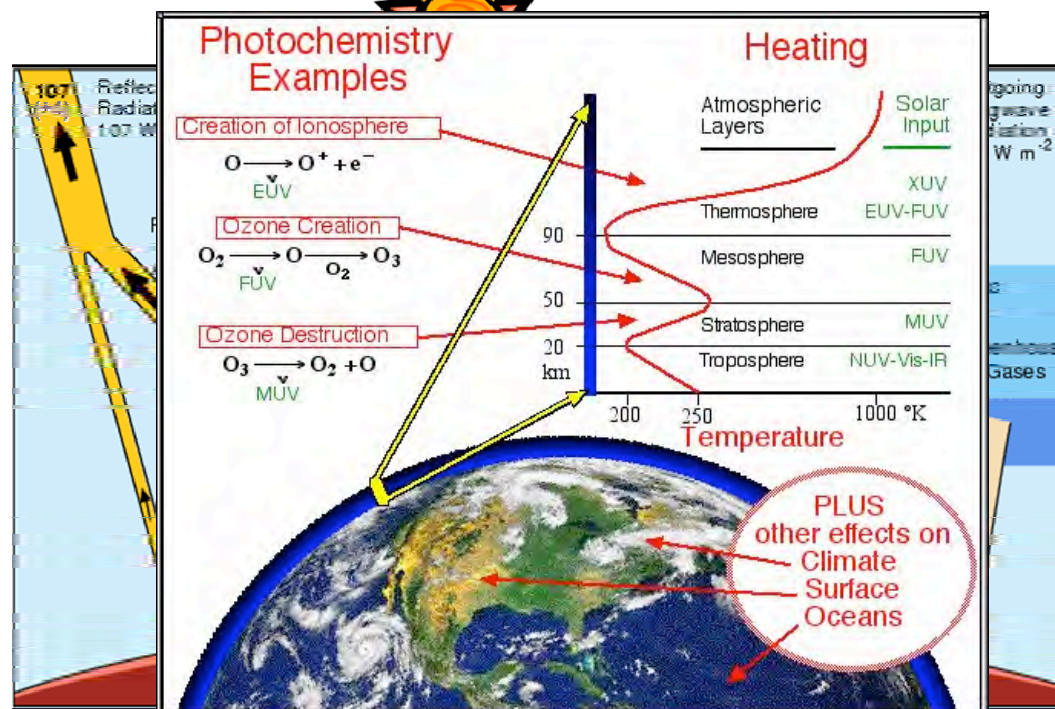
NCAR WACCM [Marsh et al., 2007]

HAMMONIA [Schmidt and Brasseur, 2006]

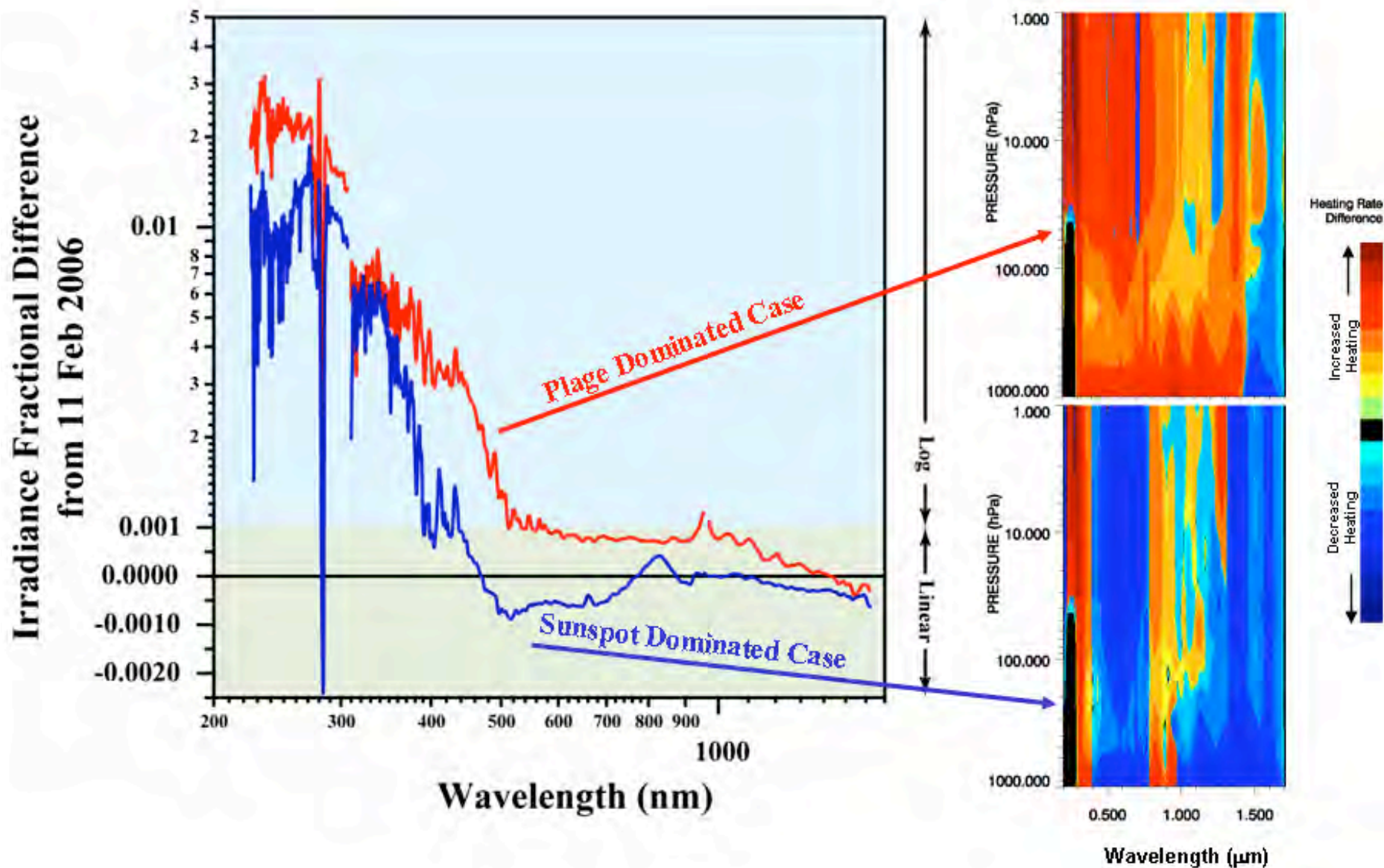
CMAM [Beagley et al., 1997]



[Adapted from P. Pilewskie,  
Solar Physics, 2005]



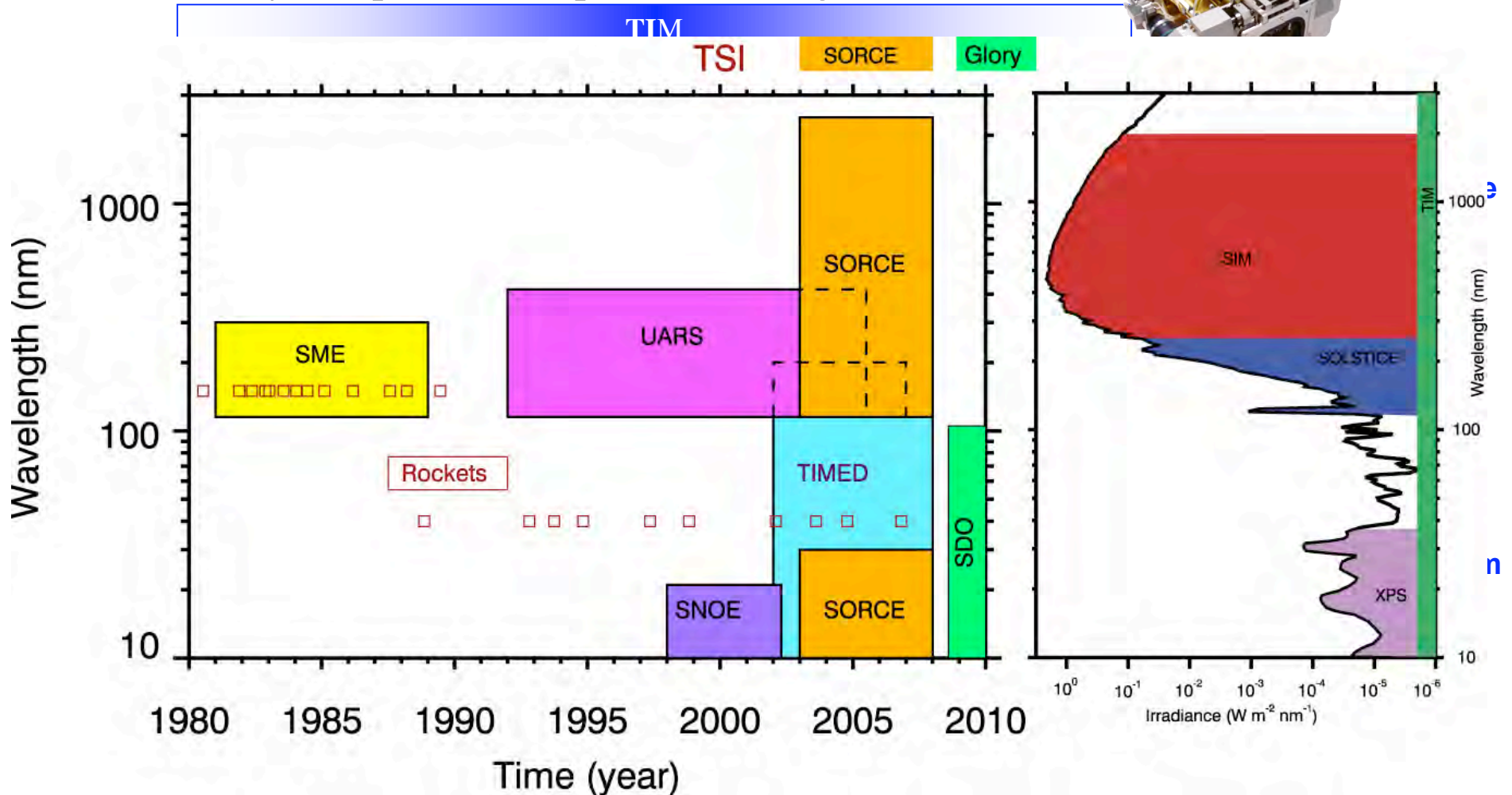
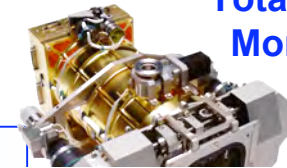
# Atmospheric Heating Rates Depend on Spectral Irradiances



# SORCE and TIMED Measure Irradiance Across Spectrum

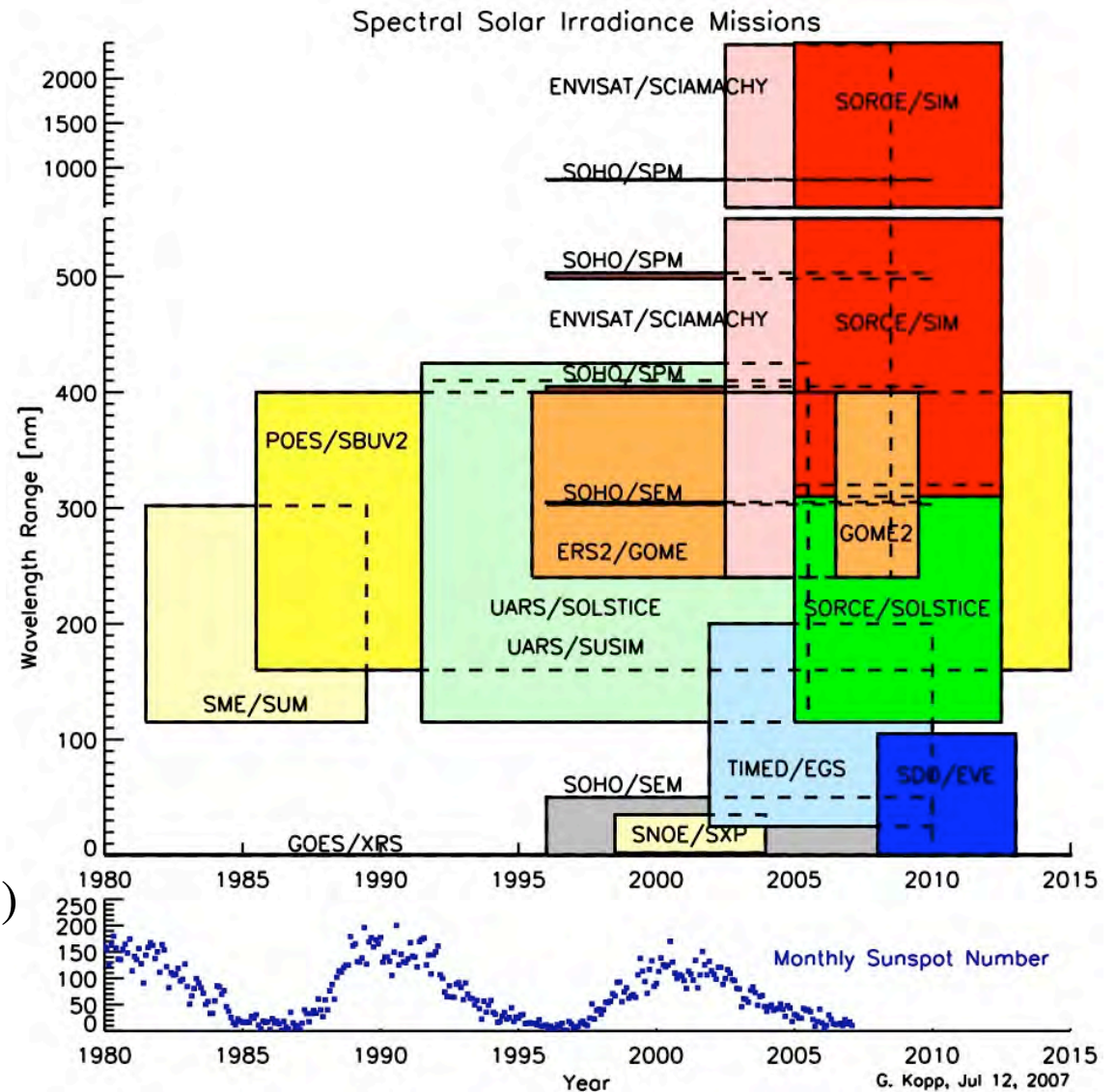
- Solar irradiance measurements since March 2003
- Nearly complete solar spectral coverage

**Total Irradiance Monitor (TIM)**



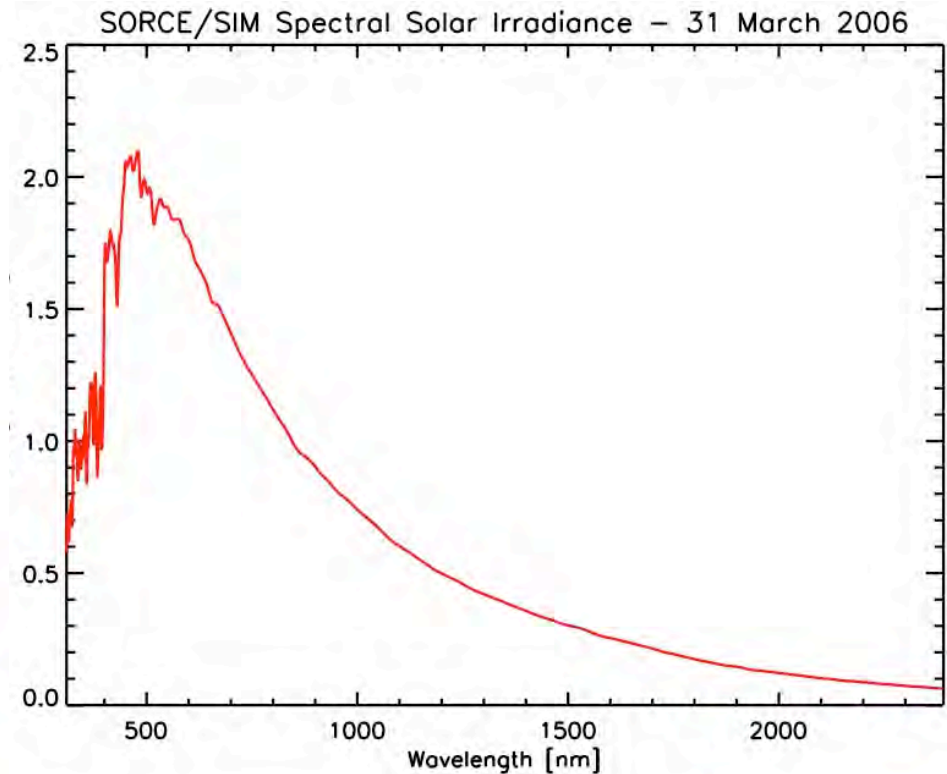
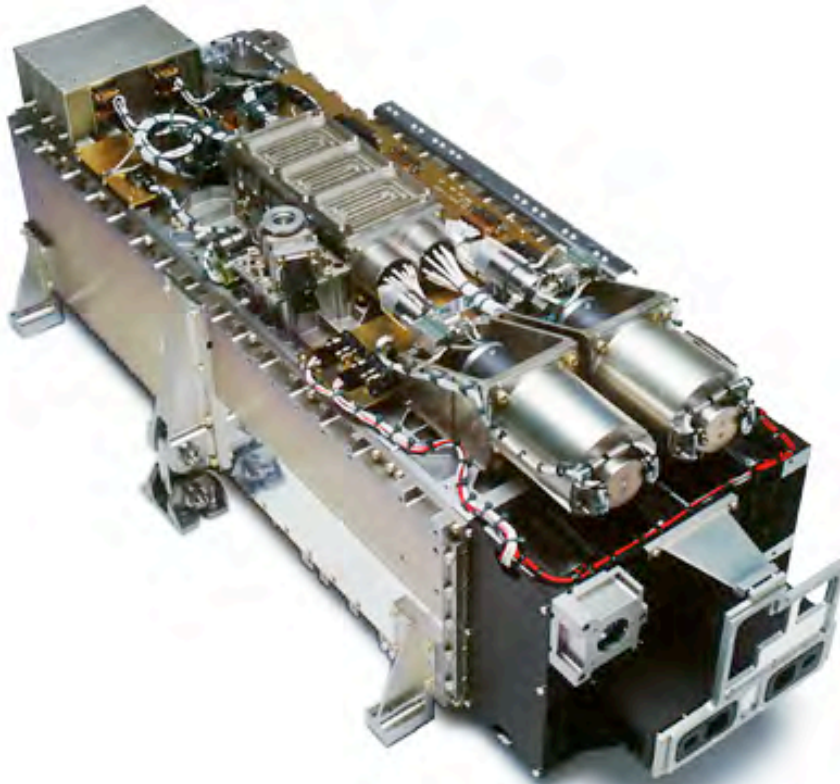
# Solar Spectral Irradiance Measurement Summary

- GOES XRS (1975 - )
- POES SBUV (1985 - )
- SME (1981 - 1990)
- UARS (1991 - 2005)
- GOME (1995 - )
- SOHO SEM (1996 - )
- SOHO VIRGO SPM (1996 - )
- SNOE (1998 - 2003)
- TIMED (2001 - 2008)
- SORCE (2003 - 2009)
- GOES EUVS (2006 - )
- SDO EVE (2008 - 2013+)
- NPOESS ? SIM (2013 - )



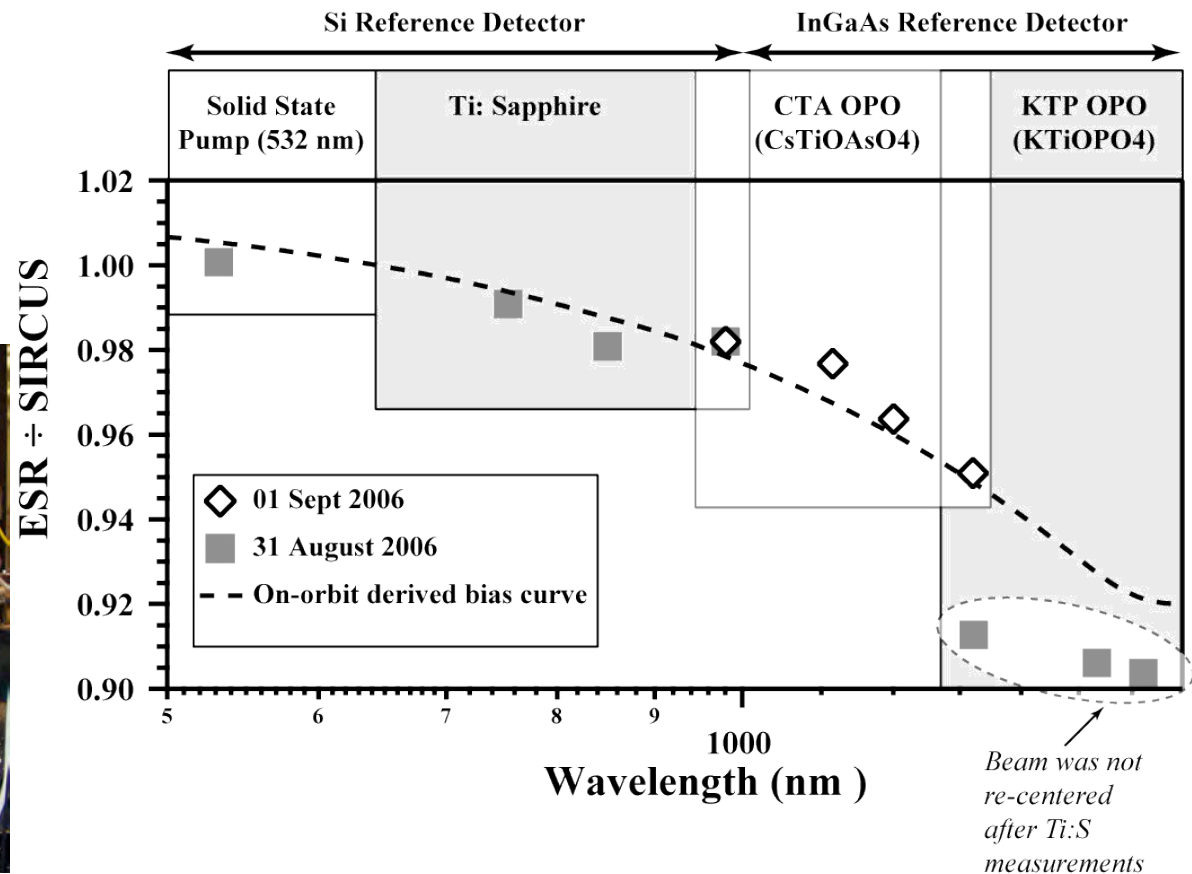
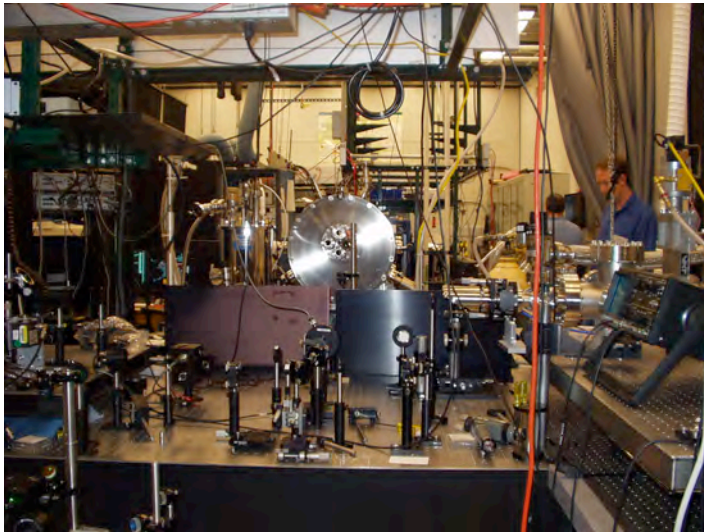
## The SIM Acquires Daily Solar Spectra

- This is the best calibrated solar spectral irradiance instrument acquiring regular spectra
  - 310 - 2400 nm
  - 2% accuracy



# NIST SIRCUS Calibrations Will Improve Future SIMs

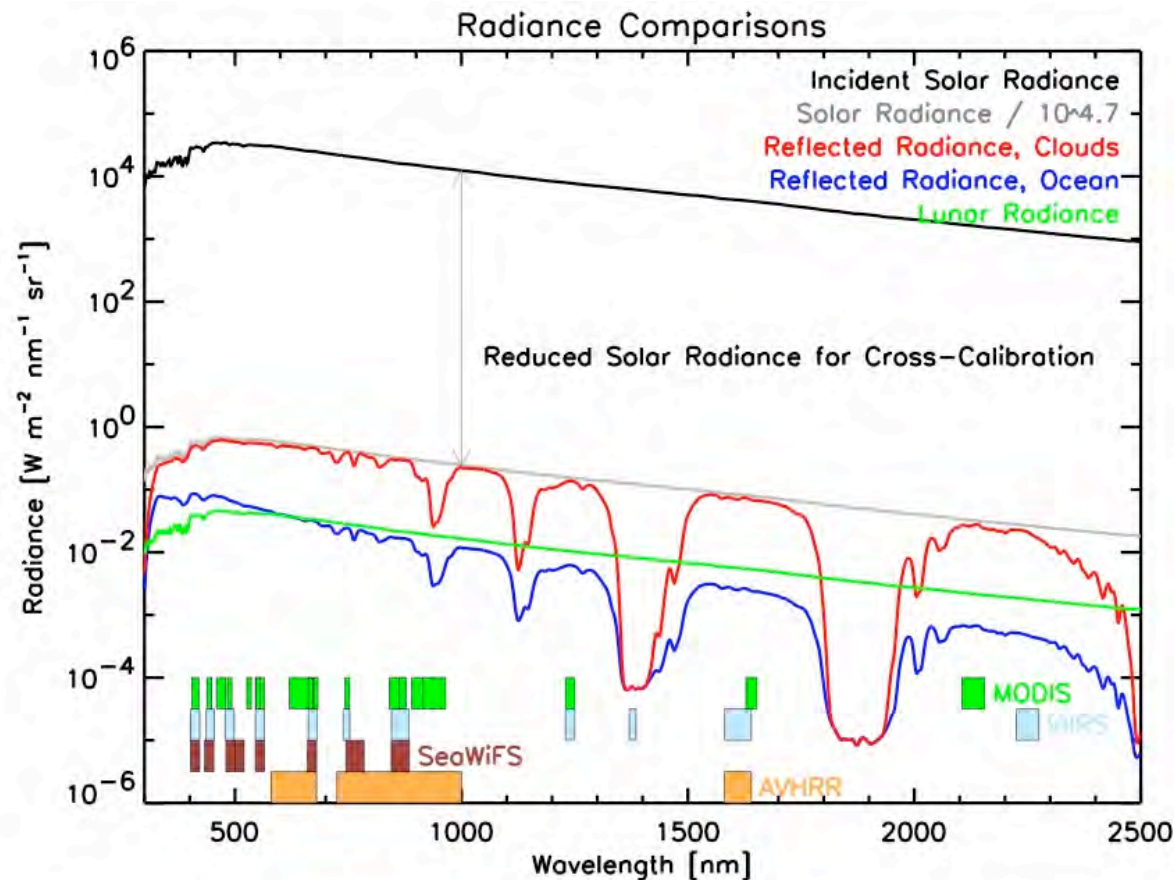
- Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) tests on SORCE/SIM radiometer alone improved efficiency knowledge
- *$\sim 0.1\%$  accuracy possible with such end-to-end calibrations*



# Validate Earth Viewing Instruments From Accurate Solar?

- Cross-calibrating Earth viewing instruments off solar irradiance instruments provides on-orbit calibration or independent validation.

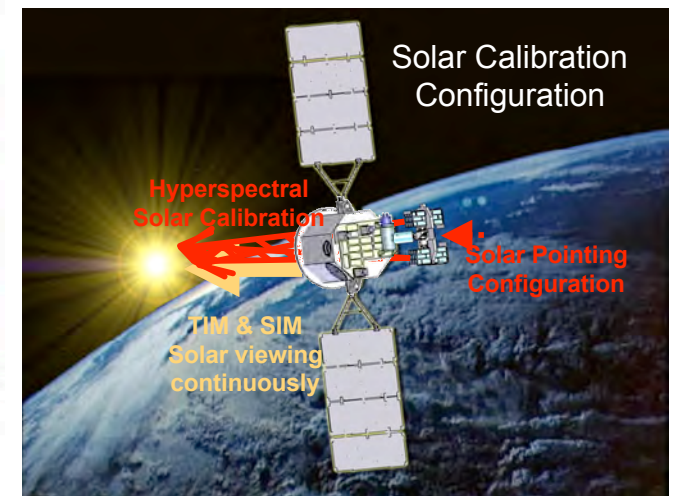
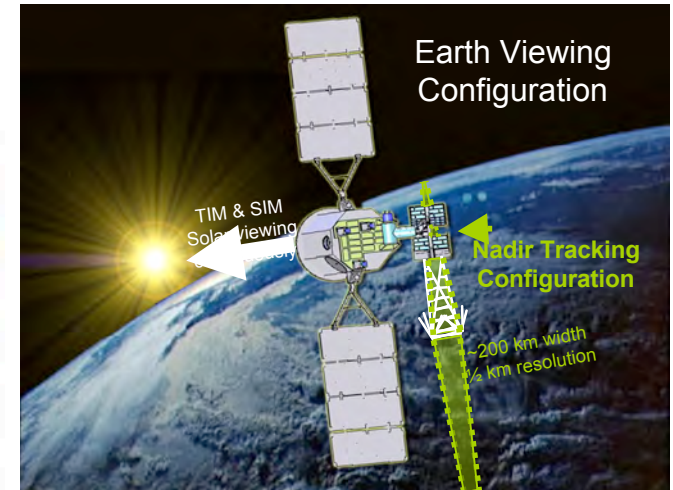
*Pointing system allows hyperspectral imagers to view the Earth or the Sun for calibrations.*



See "An On-Orbit Cross-Calibration Approach for CLARREO Hyperspectral Imager" poster

17 July 2007

Solar Irradiance Calibrations



Greg Kopp, p. 24

# Solar Irradiance Calibrations: Conclusions

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- Calibration accuracies
  - TSI
    - Progress is being made toward 0.01% absolute accuracy
    - Ground-based calibration facilities provide baseline for future instruments
    - Desired stability has been achieved
  - SSI
    - 0.1% likely achievable with NIST SIRCUS calibrations
    - 300 - 2400 nm
- Solar Irradiance Uses
  - Total solar irradiance used for climate sensitivity studies by extending 30-year data record and understanding solar variability
  - Solar spectral irradiance measurements needed to model Earth's atmospheric response and solar variability
  - Absolute accuracy of radiative balance